Flight Testing a Wing for a Formula One Race Airplane

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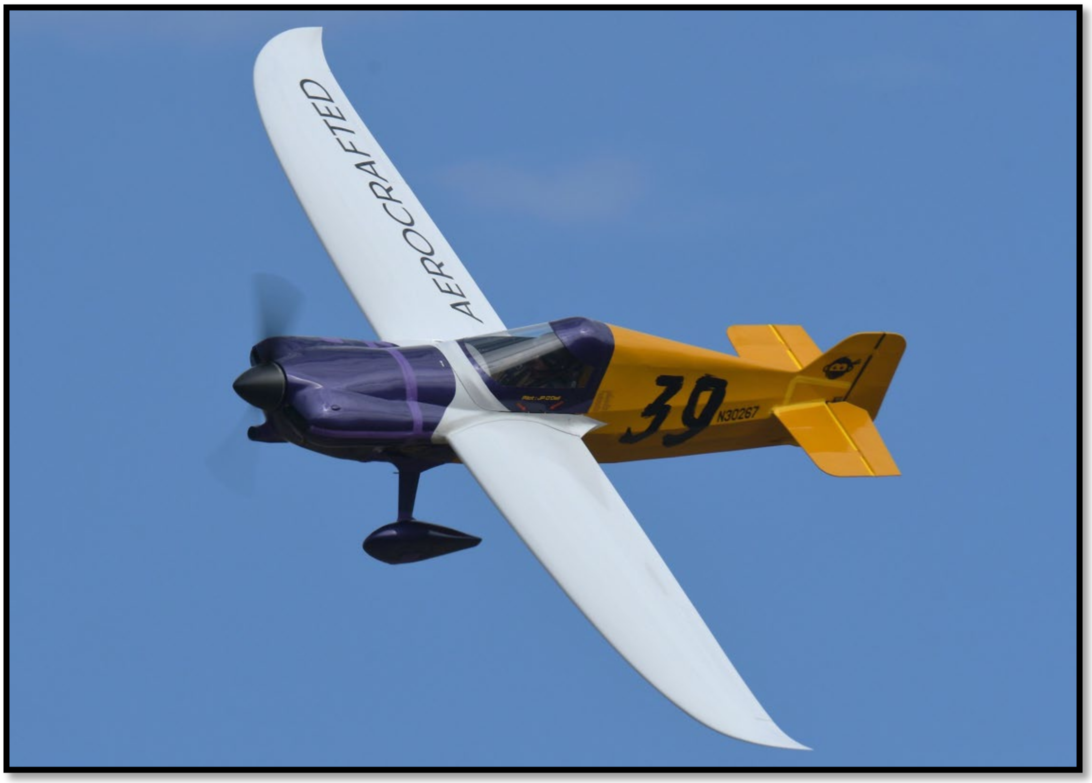
Engineer/Builder/Project Pilot



The experimental homebuilt Cassutt IIIM, nicknamed "Monkey Ninja", started and completed its phase I flight testing in July 2023 after changing the main wing to a new, custom model designed by Dr. Paulo Iscold and built and tested by the author. The new wing differed significantly from the stock Cassutt wing, featuring an aerodynamically elliptical planform, higher aspect ratio, and carbon fiber composite construction. The entire build of the wing was completed at the Cal Poly Airplane Prototyping Lab in San Luis Obispo, CA from November 2022 to June 2023. The wing was then transferred to Mojave, CA when it was integrated into the Cassutt airframe and ran through a series of ground and flight tests which included flutter testing, Nz expansion, flying quality evaluations, wing incidence tuning, and stall testing. In September 2023, the author raced Monkey Ninja with its new wing in the Reno Air Races where he placed 3rd in the Silver class. Additional follow-on testing focusing on lateral directional flying qualities was performed in mid 2024 and characterized the directionally unstable qualities of the aircraft.

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NOMENCLATURE

α = *Angle of Attack*
β = *Angle of Sideslip (+ is wind in right ear)*
δ_R = *Rudder Deflection (+ is trailing edge right)*
AGL = *Above Ground Level*
CAD = *Computer Aided Design*
CAS = *Calibrated Air Speed*
C_L = *Global Lift Coefficient*
CNC = *Computer Numerical Control*
F_R = *Pedal Force (+ is right pedal)*
FAA = *Federal Aviation Administration*
FE = *Finite Element*
ft = *Feet*
g = *Gravitational Acceleration*
GPS = *Global Positioning System*
HQR = *Handling Quality Rating*
k = *Factor proportionate to* C_L
IAS = *Indicated Air Speed*
IF1 = *International Formula One*
INS = *Inertial Navigation System*
ISA = *International Standard Atmosphere*
LB = *Pound*
MAC = *Mean Aerodynamic Chord*
MPH = *Statue Miles Per Hour*
MSL = *Mean Sea Level*
Ny = *Acceleration in the aircraft body frame in the spanwise direction*
Nz = *Acceleration in the aircraft body frame in the vertical direction*
OML = *Outer Mold Line*
RARA = *Reno Air Racing Association*
SHSS = *Steady Heading Side Slip*
TAS = *True Air Speed*
V_H = *Maximum Speed In Level Flight*
V_{RACE} = *Anticipated Race Speed*
V_S = *1G Stall Speed In Race Configuration*

INTRODUCTION

This report will focus on the flight test program of a new, elliptical wing built for a Formula One race aircraft. Background information, outside the test aspect of this project, will also be briefly discussed to give the reader context into the author's involvement with the wing through the design, build, integration, test, and operation phases of the project. An account of the flight test planning, execution, and results will be reported and put in the context of aircraft readiness for pylon air racing.

In April 2022, the author acquired an unmodified Cassutt IIIM, nicknamed "*Monkey Ninja*", with the intention of using the airplane to collect data for various flight testing, sharpen his pilot skills, and ultimately fly in the Reno Air Races. Unknown to the author at the time he bought the airplane, one of his college professors and mentors, Dr. Paulo Iscold had designed and built a few wings for formula one aircraft with propeller designer and builder, Craig Catto. The "Iscold-Catto" wing was outfitted on formula one Gold racers such as *Limitless* and *Miss Min*.

During the 2022 Reno Air Races, the author raced *Monkey Ninja* in the formula one class. Out of 13 racers, team Monkey Ninja placed last with a qualifying speed of 174.8 MPH. After the races, the author and Iscold came up with a plan to improve the airplane's speed with a new wing. Because the molds for Iscold's old wings did not exist anymore, all new tooling would need to be made, which opened possibilities for design changes.

In November 2022, design changes had been finalized and construction began on the new wing at the Cal Poly Airplane Prototyping Laboratory at the San Luis Obispo Regional Airport (KSBP). Because of the author's and Iscold's connection to the local university, Cal Poly – San Luis Obispo, the author recruited a group of students who ended up being instrumental in helping complete the wing build on time.

In early June 2023, the author and his team had completed construction of the wing. The team executed a static load test in San Luis Obispo and then transported the wing back to Mojave, CA, closer to the author's house and flight test area for final integration and testing. The author designed and built the rear wing attach mechanism to interface with the existing Cassutt fuselage mounts, as well as a modified aileron control system to interface with the new wing.

On July 16th 2023, the new wing took flight for the first time with the author at the stick. During phase 1 of the test program, the envelope was expanded to Nz -1/+6 and speed to 253 MPH TAS. Maneuvers to simulate expected loading and conditions during a race were tested and deemed acceptable to enter in the Reno Air Races. In September 2023, the Monkey Ninja team placed 3rd in the Silver class with a maximum lap speed of 208 MPH.

Due to interesting flying qualities uncovered during phase 1 testing, the author performed additional testing in mid 2024 using more thorough instrumentation. This "phase 2" testing consisted of 6 flights aimed at characterizing lateral-directional flying qualities of the aircraft.

MISSION DEFINITION

The Cassutt IIIM's primary mission is pylon air racing. This type of air racing involves maneuvering around markers on the ground, known as pylons, at altitudes of 50 ft to 200 ft. The pylons are generally positioned in an oval shape, resembling a racetrack. Pylon air racing is a "head to head" sport, which means up to eight aircraft are simultaneously maneuvering around the same set of pylons. The Cassutt IIIM has historically competed in pylon air racing events in the "Formula One" class, which limits racers to a common set of requirements such as a minimum wing area of 66 ft^2, a normally aspirated Continental O-200 powerplant, fixed pitch propeller, and fixed main landing gear. The organization governing rules and regulations related to formula one air racing is the "International Formula One Pylon Air Racing Inc" (IF1).

It is obviously important for formula one aircraft to be optimized for maximum speed around the race course. Because all aircraft in the class are limited to using the same powerplant, the success of the aircraft are largely based on the efficiency of the airframe. Surfaces such as the vertical stabilizer and horizonal stabilizer are often made as small as practical to reduce drag, at the expense of degraded flying qualities. Subsystems such as elevator trim and steerable tailwheels are often omitted to reduce weight, at the expense of operational complexity.

Operating at low altitudes, high speeds, in close proximity to other aircraft, and around a precision course demands certain predictable flying qualities from the race aircraft. Flying quality tests that were performed were evaluated against Category A flight phases per MIL-F-8785C.

TEST ARTICLE DESCRIPTION

The aircraft under test was a Cassutt IIIM, outfitted with a stock fuselage, empennage, canopy, and cowling. An elliptical, laminar flow wing was installed as a replacement for the stock, rectangular wing. The landing gear was arranged in a tailwheel configuration. The fuselage was made up from steel tube and fabric construction and the cowling and canopy were made from fiberglass. The test article was powered by a normally aspirated, carbureted, Continental O-200A and fixed pitch propeller. The ailerons, elevator, and rudder were reversible. There was no pitch trim system that can be operated by the pilot during flight. Changes in pitch trim would be accomplished by shimming the horizontal stabilizer.

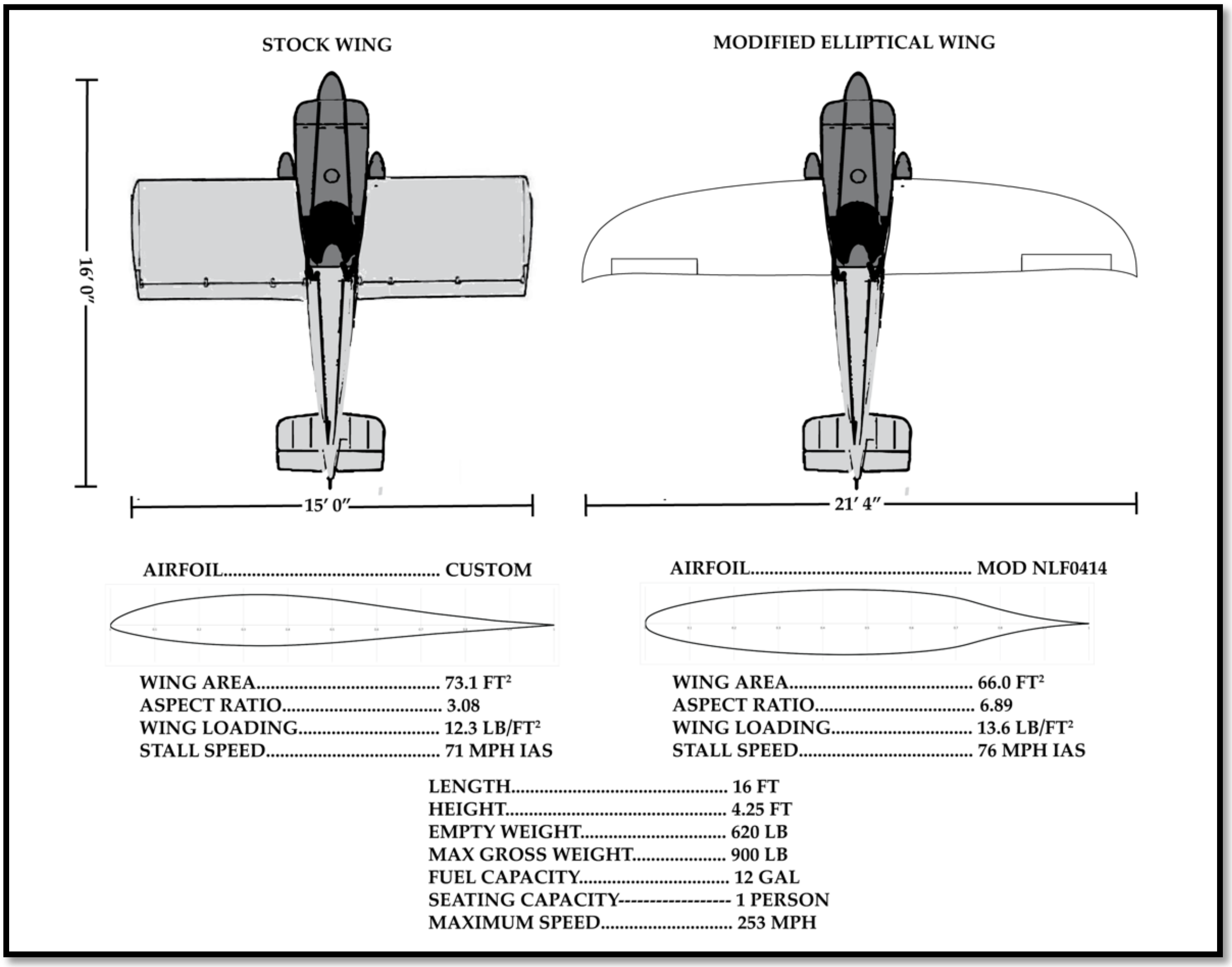

STOCK WING
MODIFIED ELLIPTICAL WING
16′ 0″
15′ 0″
21′ 4″
AIRFOIL.. CUSTOM
AIRFOIL.. MOD NLF0414
WING AREA....................................... 73.1 FT²
ASPECT RATIO.................................. 3.08
WING LOADING.............................. 12.3 LB/FT²
STALL SPEED..................................... 71 MPH IAS
WING AREA....................................... 66.0 FT²
ASPECT RATIO.................................. 6.89
WING LOADING.............................. 13.6 LB/FT²
STALL SPEED..................................... 76 MPH IAS
LENGTH.. 16 FT
HEIGHT... 4.25 FT
EMPTY WEIGHT.............................. 620 LB
MAX GROSS WEIGHT.................... 900 LB
FUEL CAPACITY............................... 12 GAL
SEATING CAPACITY----------------- 1 PERSON
MAXIMUM SPEED........................... 253 MPH

Figure 1: Old wing vs. new wing comparison

In addition to the wing change, several other subsystems had been changed and required testing during the program.

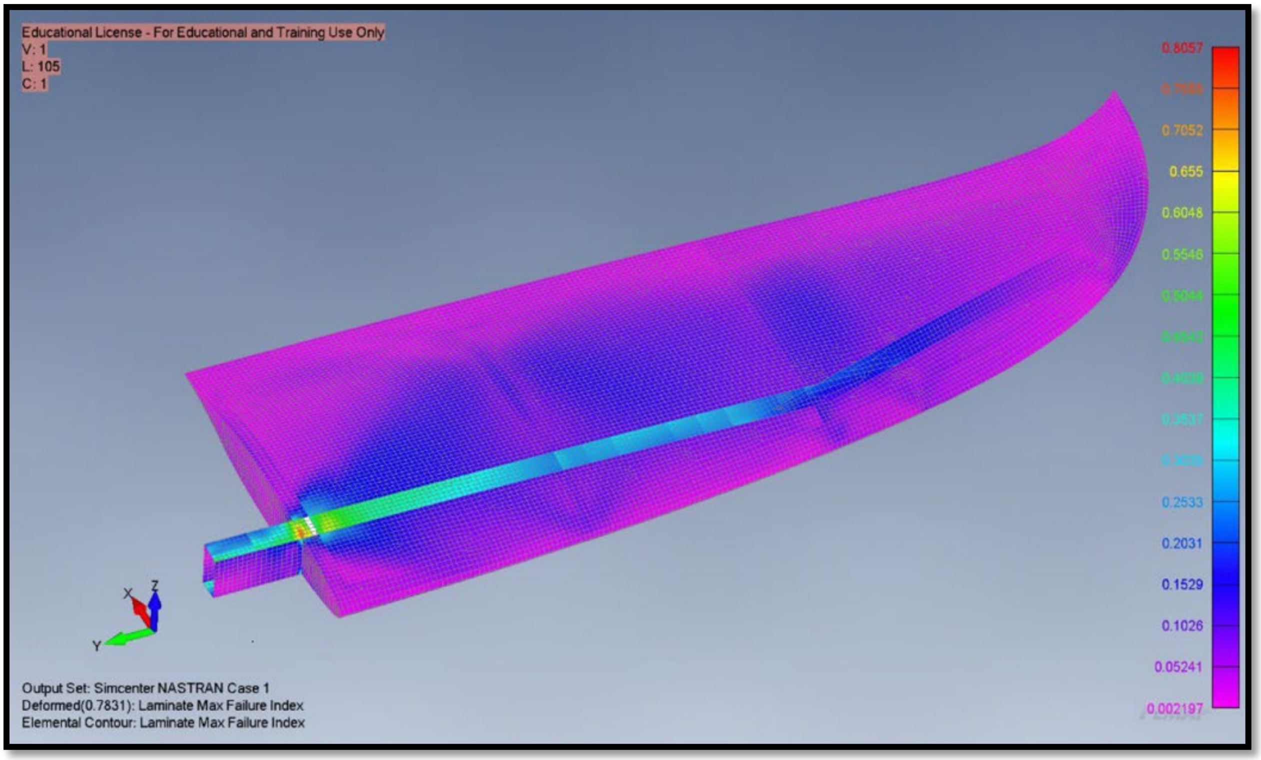
On the stock wing, the pitot tube was mounted in the leading edge of the outboard half of the wing. Due to the desire to keep the entirety of the laminar flow wing clear of any obstructions, the pitot tube was relocated to the leading edge of the right main wheel fairing. The pitot-static system was deemed unreliable until it was calibrated using flight test data. A loaner engine was installed for flight testing, due to the previous engine suffering a catastrophic failure on the last flight with the stock wing. Lastly, the aileron control system was modified to accept the new wing and was untested in flight. All these factors played a role in test planning and evaluating risk for the first flight and subsequent envelope expansion.

DESIGN

The design of this new wing was an iteration of the "Iscold-Catto" wing, sporting a couple changes to the outer mold line (OML). These changes included a fully elliptical planform, swept up wingtips, shorter (spanwise) ailerons, and a non-straight trailing edge. These changes were deemed minor enough in nature to not warrant a structural redesign.

A detailed summary about the design of the original Iscold-Catto wing can be found in Paulo Iscold's, "Design of a Wing For Formula One Category Airplanes" [1].

At a high level, the wing was designed to comply with all IF1 rules such as a wing area of 66 ft^2 and limit load of 7 g. A trajectory simulation of the race course was performed to determine the coefficient of lift at which the airplane would be operating at around the course. Based on the results, Paulo used a set of modified NLF0414 airfoils ranging from 1.4 percent camber at the root and tapering to 0 percent camber at the tip in an effort to keep the entire wing within the drag bucket. A hyperbolic chord distribution, a compromise between a fully elliptical or fully rectangular planform, was chosen to reduce induced drag while also retaining acceptable stall characteristics.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X
Z
Y
Output Set: Simcenter NASTRAN Case 1
Deformed(0.7831): Laminate Max Failure Index
Elemental Contour: Laminate Max Failure Index

Figure 2: Laminate max failure index contour from a finite element model, built by student Benjamin Fields, to verify the structural analysis already completed on the original Iscold-Catto wing. Loading conditions are conservatively estimated, using a flight condition of 300 MPH and 5°α.

BUILD

Most construction and assembly work was done at the Cal Poly Airplane Prototyping Laboratory at the San Luis Obispo airport (KSBP) due to space, machine availability, and access to help from Cal Poly students. The spar construction began in November 2022. The main spar was comprised of a polystyrene foam core, CNC machined to account for the complex changes in geometry along the wing. Unidirectional carbon fiber was then laid up on the foam to form the spar caps, which were symmetrical on the top and bottom, comprising of 32 plies at the root and tapering to 4 plies at the tip. After both spar caps had cured, bidirectional fabric biased at 45 degrees were layed up to form shear webs on the remaining two sides, resulting in a strong and stiff box spar.

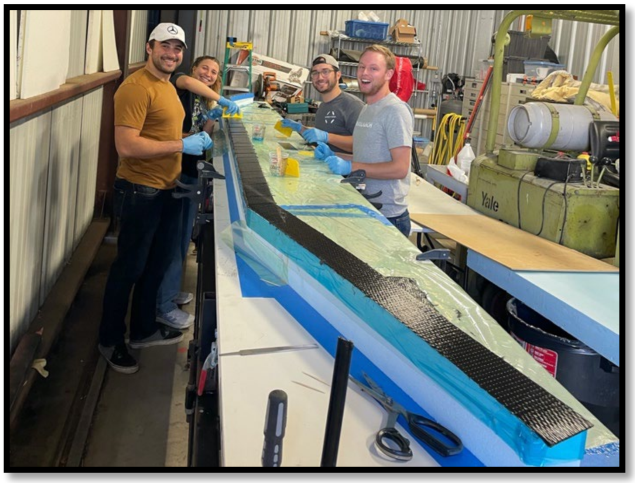


Figure 3: Ben Fields, Olivia Burd, Noah Glaser, and JP O'Dell (left to right) lay up the first spar cap using uni-directional carbon fiber on the polystyrene core.

The wing skins were constructed from non-crimped biaxial carbon fiber fabric with 95% of the fibers running at a 45 degree bias for torsional stiffness. A low-density PVC foam was used as a core to provide additional stiffness. Wet layups were performed in molds that the author cut on a large 5 axis CNC gantry from 20 lb tooling foam.

The wig ribs were constructed by making sheets of a simple flat sandwich panel, comprised of bidirectional carbon fiber and foam core, and then cutting the rib shapes on a CNC table. In areas that the aileron torque tube passed through a rib, the foam was shaved away and replaced with a machined phenolic bushing.

Once the spar, skins, ailerons, and ribs were constructed, the skin molds were fixtured in place on the ground and tracked precisely using a laser alignment system. From here, the skins were placed back in the molds and the spar was bonded into the skins. Next, the ribs, ailerons, torque tube, and other internal hardware were fit up and bonded into the skin. All aluminum parts internal to the wings were chem-filmed for corrosion protection and longevity.

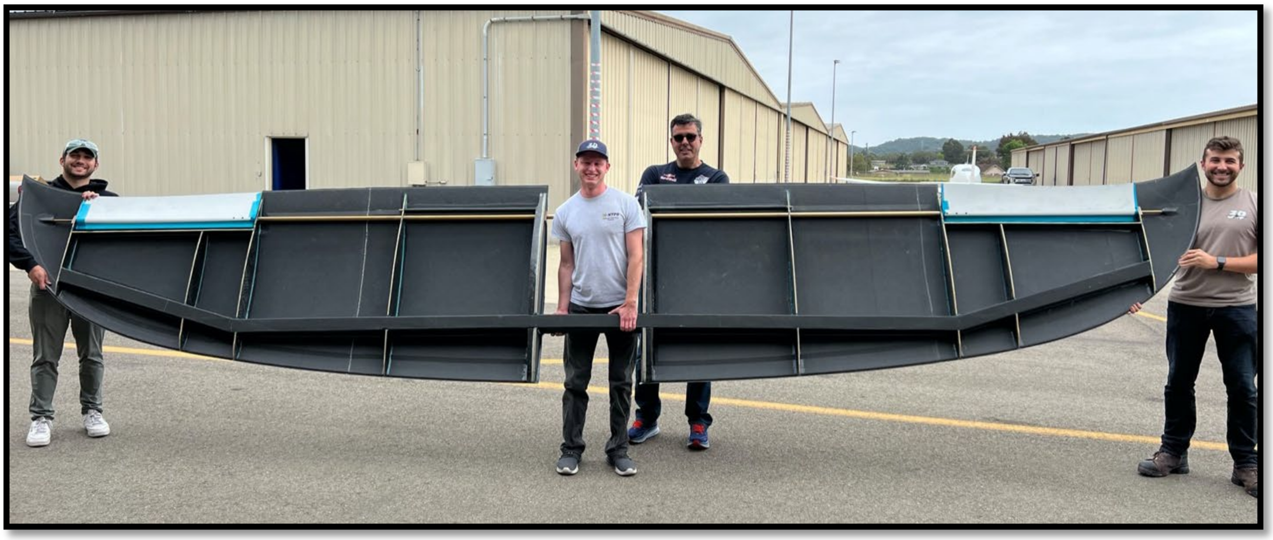


Figure 4: Noah Glaser, JP O'Dell, Paulo Iscold, and Ben Fields (left to right) hold the wing for a picture just prior to final closeout

After fit-ups, checks, and fine tuning, the other side of the skin was bonded and the wing was closed out. A 24-hour room temperature post cure was accomplished, followed by a 36-hour elevated temperature post cure in a custom oven that the author made. Following the post cure and final trimming, the wing was ready to begin integration.

The wing was brought back to the author's hometown where the integration and finishing began. Due to the large difference in root chord length between the new wing and stock Cassutt wing, the author redesigned the aileron control system to interface with the new aileron torque tube location. Using CAD referenced with a 3D scan of the fuselage, a new aileron control system was designed, built, and tested.

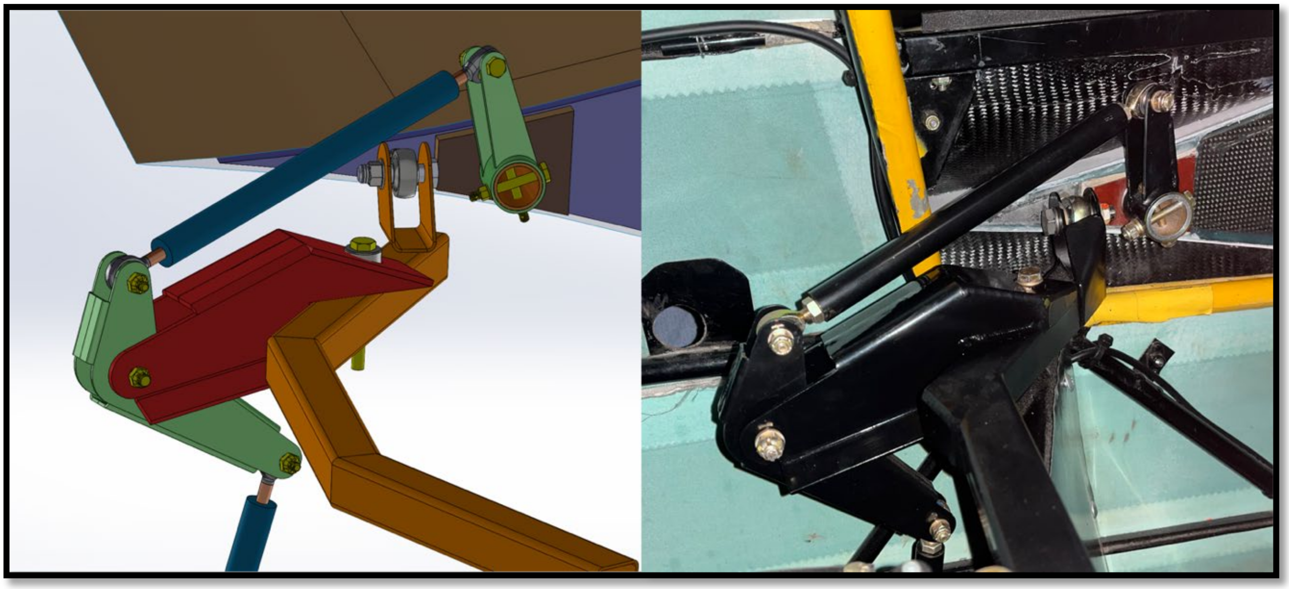


Figure 5: A side by side comparison of the CAD model vs. the as-built aileron control system and wing aft attach point

INSTRUMENTATION

Instrumentation for phase 1 of the flight test program consisted of data displayed to the pilot on the instrument panel and a GoPro camera mounted inside the cockpit to record the panel. The GoPro was also valuable for recording pilot actions, stick position, and aircraft response. The instrument panel (Figure 6) included an altimeter, airspeed indicator, g meter, inclinometer, tachometer, oil pressure/temperature, VHF comm radio, and a phone with Foreflight which displayed GPS based parameters (groundspeed, track, etc…). For collecting data to inform wing incidence tuning, a digital inclinometer was fixed to the longeron to read pitch angle.

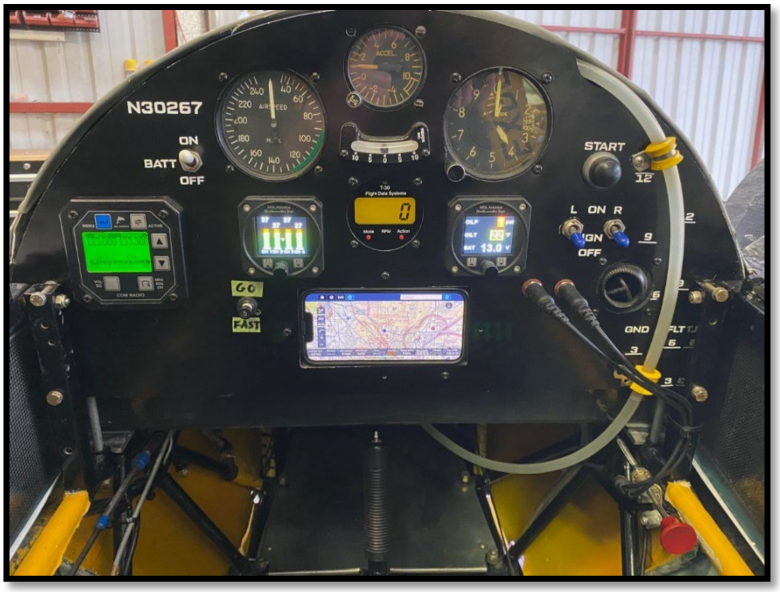


Figure 6: Instrument panel, showing all data sources the evaluating pilot had during initial flight testing

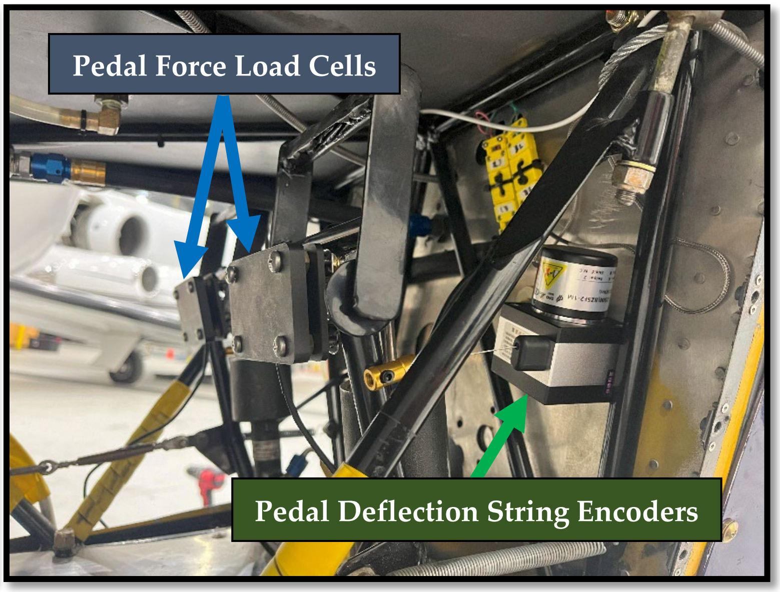


Figure 7: Pedal instrumentation installed for phase II testing, which included pedal force load cells and pedal deflection string encoders.

For phase 2 flight testing, additional instrumentation was added to better characterize the lateral directional flying qualities of the airplane. This instrumentation included a Vectornav VN-300 GNSS/INS that was used to collect data on the inertial state of the vehicle and synthetically estimate air data parameters such as sideslip angle (β). Load cells on custom brackets were implemented to collect data on pedal forces (Figure 7). String encoders were mounted on the pedals to collect data on pedal deflection (Figure 7). Since the aircraft has reversible flight controls, pedal deflection was able to be mapped directly to rudder deflection using a custom calibration curve.

EVALUATING PILOT

The pilot for all initial and envelope expansion flight tests was the author, JP O'Dell. At the time of the flight testing, the author had 1350 hours total time with 45 hours in a Cassutt IIIM with a stock wing. In addition, the author had approximately 100 hours tailwheel. The author had time logged in over 30 different aircraft types including jets, turboprops, floatplanes, ultralights, and experimental aircraft.

During the previous year, the author had completed the Pylon Racing Seminar (PRS) where pylon racing techniques were taught and applied on the Reno-Stead formula one race course. During the 2022 Reno Air Races, the author participated in four races, as well as the numerous practice and qualification laps. The author had approximately 200 laps flown on the Reno Stead formula one race course.

TEST AND EVALUATION

GENERAL

During the planning for initial flight testing, it was decided the airplane would be operated in a conservative capacity, in an effort to focus primarily on conditions seen in an air race environment. The philosophy was that the team would focus on testing the qualities that directly related to the mission definition of racing, such as structural integrity, flutter, and certain flying qualities. Other aspects like takeoff/landing distances, climb performance, etc were not focused on during initial testing. This was justified by imposing strict operational restrictions until further testing could be completed. Restrictions such as being in glide range of an airport, always having ground support available, using excessively long runways, and testing in areas of minimal terrain were implemented for initial testing. This desire to operationally restrict the aircraft during testing was exacerbated by a catastrophic engine failure three months prior with the stock wing still installed, resulting in the author performing a forced landing on a rural highway. Due to the aggressive schedule and risk associated with this testing, these operational restrictions were imposed and adhered to throughout the test program.

A set of 12 objectives, listed in Appendix 1, were derived to satisfy all applicable FAA, IF1, and RARA requirements. [2,3,4]. On top of the necessary requirements, the author added an additional 18 objectives based on pilot and engineering judgement related to safely operating this airplane in a racing capacity. The additional requirements were based on previous racing experience, AC-90-89C [5], and applicable parts of MIL-8785C [6]. A list of requirements for the test program can be found in Appendix 1 and 2. Requirement F2.4.4 was not satisfied due to marginally acceptable directional flying qualities, discussed further in the *Flying/Handling Qualities* section.

Figure 8: Ground crew member, Kevin Bickers, helps the pilot perform control checks prior to takeoff.

Airport selection was an important consideration and Mojave Air and Space Port (KMHV) was chosen to be the home of all flight test activities for this project. Approval was received from the FAA to include the area around KMHV for the duration of the flight test campaign. MHV has 3 runways (one over 12,000ft long), usually calm weather in the mornings, and was located in a very unpopulated area. During testing, the control tower and crash/fire/rescue (CFR) was notified of planned test events since much of the planned operations were non-standard and better pre-briefed.

As mentioned earlier, at least one ground crew member was required for all flight tests. This requirement was driven off a couple factors:

1) Due to the pilot’s high workload even during a normal flight in the Cassutt, having someone on the radio to write down data and observations was necessary.
2) A runway excursion or loss of control on the ground could lead to the aircraft flipping over, which would lead to a difficult or impossible pilot egress. The ground crew was trained in pilot recovery procedures and was always equipped with a radio, 4wd car, fire extinguishers, window breakers, and first aid kits in the event of an incident.
3) Due to the size of KMHV, the trip to the primary runway from the hangar was over 2 miles. The crew exclusively towed the aircraft to the end of the runway, rather than taxiing to avoid long engine run times.

The use of a chase aircraft was also another consideration in the test planning. A chase aircraft can be beneficial if you have an experienced chase pilot. Adding another airplane to the test can also unnecessarily complicate things, so it’s important to weigh the risks and benefits. For the first flight, it was determined that chase could provide insight to the condition of the wing, check for fluid leaks from the new engine, observe control deflections, and deconflict radio comms for the pilot. The chase pilot was also an experienced pilot, test pilot school graduate, and in a comparably performing airplane. It was determined that chase would be required for the first flight, but not necessary on subsequent flights.

GROUND TESTING

STATIC LOAD TEST

The first step in the test sequence was a structural load test on the ground. Since flight testing requirements specified +6 g in flight, a static load test of to the design limit load of +7 g on the ground was desired. A load test box was constructed out of lumber and steel, which simulated the interfaces on the airplane to ensure loads were being transferred between the box and wing in a flight representative way. Using the loads that were inputted to the finite element (FE) model, an equivalent distribution using sandbags to apply the load was calculated. Due to the discrete nature of sandbags, the loading condition of the test over-simulated bending loads by ~9.1 percent, while shear loads were consistent with the model, ultimately resulting in a conservative test. Over 4500lbs of sandbags were loaded on the lower surface of the wing and the condition was held for 2 minutes. In the loaded condition, the tip deflection was measured to be 3.3 inches. The actual deflection was compared to the FE model and was approximately 10% greater than the calculated deflection, which the team felt was acceptable given error source such as the higher bending moment, accuracy of the tip deflection measurement devices, and deflection of the support structure. After removing the sandbags, the tip returned to its original position immediately, giving the team confidence that there was no perceivable internal damage to the structure and the wing was ready to begin integrated test.

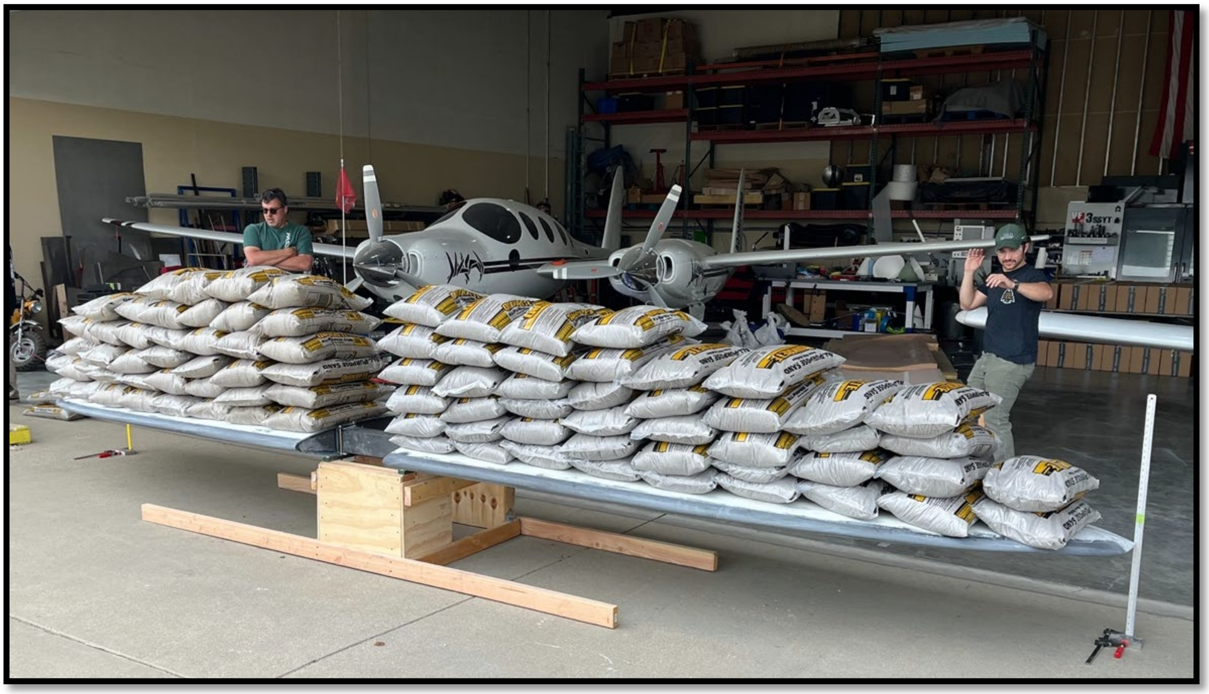


Figure 9: Static Load Test Simulating ~7.0 g on the Structurally Complete Wing

TAXI TESTING

Before the first flight, a series of low and medium speed taxi tests were planned to check ground handling and provide pilot proficiency training. It was also an opportunity for the pilot and ground crew to practice towing the airplane out to the runway, work with the control tower, and practice for flight day. Two tests were completed to 20-30 MPH to practice raising and lowering the tail and compare to the previous wing configuration. No anomalies or notable differences were noted.

Then, two tests to 60 MPH (80% of anticipated V_S) were completed to check aileron response and medium speed ground handling. No adverse behavior was observed, and aileron response was positive at these speeds. Aileron authority was strong enough to input a few degrees of roll with both wheels on the ground, just from compressing the gear legs. After the taxi test, the airplane and pilot were ready for the first flight.

FLIGHT TESTING

FIRST FLIGHT

On July 16, 2023, the team assembled before sunrise and did a final checkout on the airplane. The primary objective of the first flight was to prepare for landing. The flight would consist of an airborne pickup with the chase aircraft, a modified climb out over the airport while checking control responses in all 3 axes, a pacer check with chase to test a new pitot-static system that had been installed, a trim evaluation, and a series of controllability checks while decreasing airspeed incrementally to determine the approach speed. The maximum indicated airspeed was limited to 160 MPH for the first flight, until proper flutter testing could be performed.

During the initial test planning, the team evaluated the best approach to the first flight. One approach to the flight was the “short hop” which involved taking off, staying close to the runway for a couple seconds, and then immediately landing straight ahead to evaluate the landing as one of the first test events. The other approach was to takeoff and climb away from the ground to a safe altitude as quickly as possible, and then evaluate aircraft handling. A “short hop” flight was deemed risky due to the workload of a takeoff, limited initial flying quality assessment, and landing in a short amount of time. The workload combined with the ground handling difficulties of the Cassutt, made the “short hop” option unacceptable.

To justify a normal takeoff and climb and ensure the aircraft would be safe to operate until a normal landing could be made, a set of criteria for an aborted takeoff were briefed and were to be evaluated by the pilot upon lift off. Those abort criteria were…

- Excessive aft stick force
- Any forward stick force
- Stability or control in question
- Unexpected engine or airframe vibration

The first takeoff was completed uneventfully, developing an estimated 6-10lb of aft stick force at 100MPH (rotation speed). The pilot deemed this acceptable and continued the takeoff and climb out.

After level off at 7000′ MSL, a clean and dry check, pacer check, and trim evaluation was quickly accomplished. Then, a series of control checks in all 3 axis were performed. Rudder ramps and releases were used to evaluate directional stability and steady heading side slips (SHSSs) to a wing pickup were used to assess static lateral-directional stability. Weak directional stability was noted when pedals were released. Each of these tests were completed at decreasing airspeeds until the pilot determined a minimum safe airspeed, which ended up being 100 MPH. The minimum safe airspeed was not based on an approaching wing stall, but rather excessive aft stick force and position. An approach speed of 1.3 x minimum safe speed was set at 130 MPH.

During the first attempt at an approach and landing, the aircraft had an excessive nose-high attitude in the flare. At approximately 105 MPH, the wheels touched with minimal vertical velocity, but immediately began a “jouncing” motion due to the tailwheel striking the ground. The unfamiliar nose high attitude, combined with the excessive aft stick and initial bounce resulted in a pilot induced oscillation that quickly became uncontrolled. The pilot initially added approximately 30% available power in an attempt to smooth out the landing, but quickly determined the power addition would not be enough to safely salvage the landing. Full power was added and a go-around was initiated. Immediately upon the application of full power, the airplane stabilized in ground effect and accelerated to 120 MPH before a normal climb out and traffic pattern was made. The pilot decreased

Figure 10: A picture from "Chase" during a clean and dry check on Flight 01

the approach speed to 120 MPH (1.2x minimum safe speed) and retried the landing again, with an understanding the sight picture was different and a conscious effort to keep the tailwheel off the ground. The second landing was made uneventfully.

After post flight review, it was determined that the tail incidence was inadequately set. The set incidence required constant aft elevator input and resulted in a limited effective nose-up elevator deflection. This limited elevator forced a fast approach speed to keep elevator authority, which was a contributing factor to the aborted landing.

In addition, it was determined that the wing incidence was inadequately set (a known risk going into the flight). The wing incidence was set such that the leading edge was too far nose down. This resulted in a "3 point" attitude at approximately 120 MPH. The unfamiliar landing attitude for the pilot, coupled with a high energy state due to the tail incidence angle, contributed to the bounce and subsequent pilot induced oscillation during the first landing attempt.

WING INCIDENCE

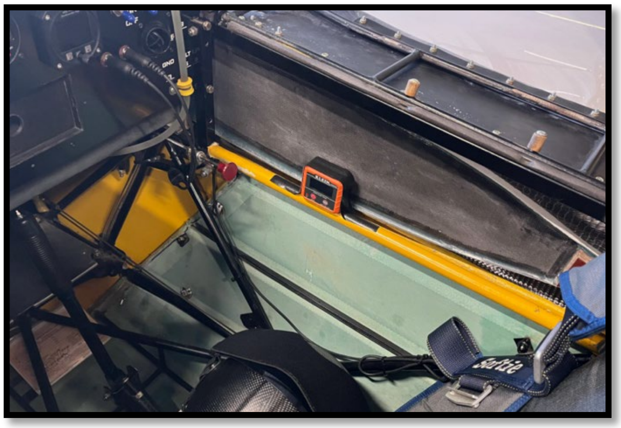


Figure 11: A magnetic digital inclinometer was stuck on the longeron and taped for safety to measure fuselage incidence during flight.

The methodology for setting wing and tail incidence was to adjust the wing incidence such that at race speeds, the angle of attack of the fuselage would be zero (theoretically minimum drag and minimum propeller asymmetry). Then the tail would be adjusted to provide the desired elevator trim force of 1-2lbf forward at race speeds. In order to find the optimum wing incidence, a digital inclinometer was fixed to the longeron in the cockpit in view of the pilot. Then, the pilot flew steady, level tracks at airspeeds from 150 MPH to full throttle (approximately 180MPH) . At each of these speeds, the pilot reported the fuselage angle of attack and indicated airspeed to the ground crew. Because a racing propeller is expensive and usage should be limited, anticipated race speeds with a sport propeller could not be achieved in level flight. A method to extrapolate fuselage angle of attack at higher speeds was constructed.

Because the global lift coefficient, C_L ,is proportionate to angle of attack, a factor proportionate to C_L (k) was used to estimate the angle of attack at the race speeds that we are unable to achieve in level flight. Plotting k against the flown fuselage angle of attack and extrapolating to the expected race k will result in the anticipated fuselage angle of attack angle at expected race speed. After two flight test iterations of wing incidence, it was determined that a 1.4 degree leading edge up angle on the wing would give zero fuselage angle of attack at 220 MPH. From this, the tail incidence was adjusted to give a slight nose-up pitch response at 220 MPH, a favorable condition for racing.

$$Factor\ proportionate\ to\ C_L = \frac{1}{V^2} = k$$

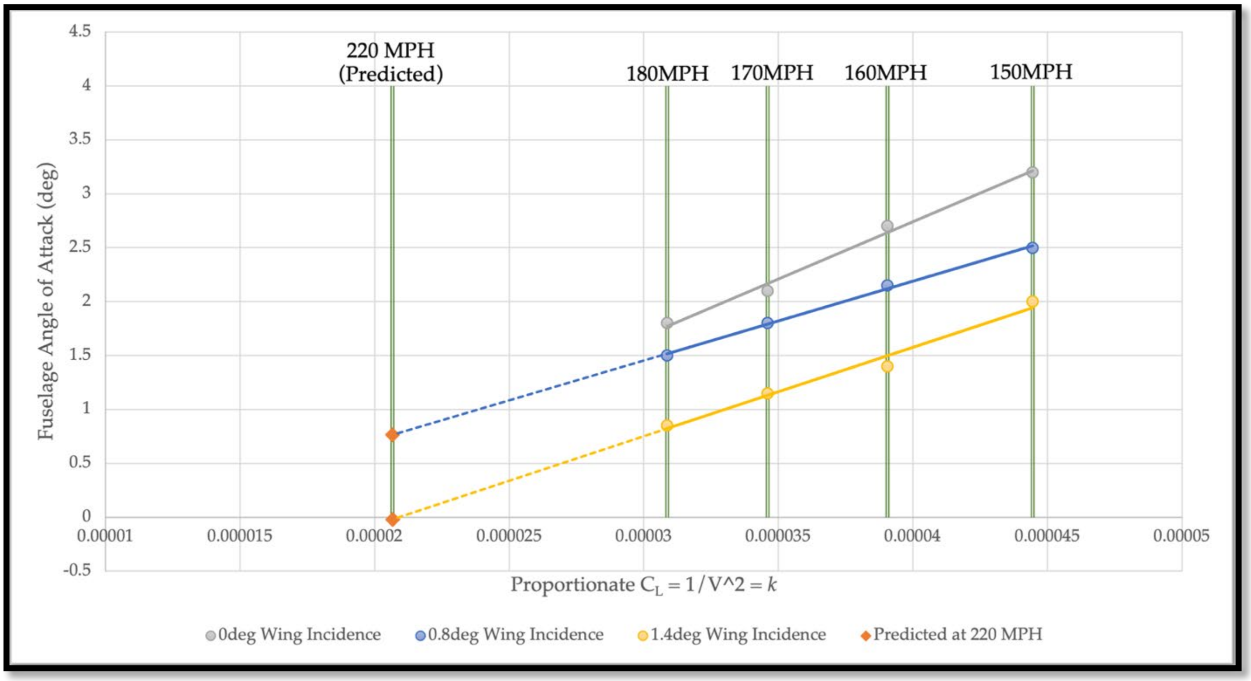


Figure 12: Wing Incidence Tuning Flight Test Data

FLUTTER

To expand the speed envelope, the primary risk was flutter. Resistance to flutter was a major design consideration with this wing, but needed to be verified through flight test. Prior to flight testing, the ailerons were 100% statically balanced and an additional check using the "Simplified Flutter Prevention Criteria" [7] was performed to ensure the wing and ailerons would analytically be free from flutter. The "Flight Flutter Test Techniques At ARL" [8] document was used as a guide to build the flight test plan for flutter. The first step was determining the most critical flutter condition that would be seen during a race. An optimistic anticipated qualifying speed for the air races was chosen to be 230MPH TAS. A margin of 10% was added to the anticipated qualifying speed, bringing the maximum test speed to 253 MPH TAS. The maximum TAS was then used to calculate test conditions in terms of CAS and altitude for the pilot to be able to easily capture test conditions. A flutter matrix (Figure 12) was created with test points beginning at conditions at which flutter was very unlikely (point 1) and proceeded through points of increasing flutter risk until the most critical point was reached (point 12).

The flutter matrix was calculated at international standard atmosphere (ISA) conditions and all flutter testing was completed at temperatures of ISA+10 to ISA+25. This adds an additional conservative margin to the testing, resulting in test true airspeeds higher than calculated true airspeeds.

Due to lack of instrumentation capabilities and the relatively low risk nature of flutter on this wing due, there was no dedicated flutter instrumentation aside from pilot observations. Flutter risk was deemed low due to special design considerations limiting torsional deflection and previous racing heritage on similarly constructed wings.

For each test point shown in Figure 13, the pilot dove to obtain the desired airspeed at the desired altitude. The pilot dove 10 MPH over the airspeed target and then established the airplane in a slight nose-high attitude so that the aircraft decelerated through the test airspeed. At the test airspeed (±5 MPH), the pilot performed stick raps on the desired control surface. The goal of the stick raps were to excite modes of the airframe to evaluate if an excited mode would be damped. At each condition, the pilot targeted a minimum of 5 pitch raps in each direction and 5 roll raps in each direction. Because on the time on condition was relatively short, multiple resets to condition were needed. During the flutter points, the pilot felt for any oscillatory behavior that was not damped within 1-2 cycles. The pilot also looked and listened to the wing for any cues of an undamped oscillation.

Flutter testing as described above was completed for test points 1-12 as shown on Figure 12. A qualitative assessment from the test pilot showed that during excitation attempts, no adverse characteristics were observed. All deflections were damped within 1-2 periods at all test points.

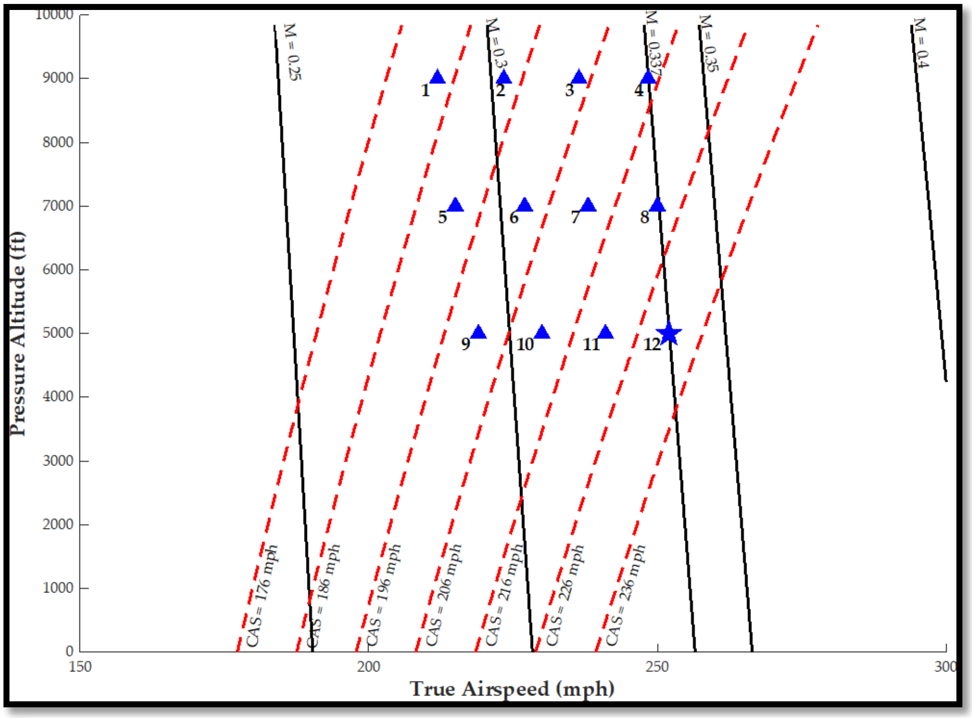


Figure 13: Flutter test point matrix

FLYING/HANDLING QUALITIES

A qualitative assessment of certain flying qualities important to a race aircraft was performed throughout the test program and was compared to the stock Cassutt wing. In addition, a series of handling quality tests were performed to understand aircraft performance in scenarios that simulated race conditions.

Pitch response was mostly unremarkable. Level, constant g turns at V_H were performed to simulate turns around the race course and altitude deviations were used as a gauge of the short period pitch response. Maintaining level flight (desired ±25 ft , adequate ±50 ft) in a 2 G, 180 degree turn, at maximum power setting, required minimal pilot compensation. The evaluating pilot achieved desired performance using constant, small elevator inputs to keep altitude constant (HQR 3). The data required to compare the test article's control feel and stability in maneuvering flight at constant speed against MIL-F-8785C [6], paragraph 3.2.2.2 were unable to be recorded; however, the control feel and stability was suitable for the intended use case. Maintaining a level turn around the race course will be easy for a trained and current race pilot, allowing adequate attention bandwidth to the pilot to focus on other tasks during a race such as engine management and formation flying.

Roll response was very crisp at all conditions, even slow speeds. Even though the ailerons on the new wing had ~2.5 times less surface area the stock wing, the steady state roll rate was almost identical at ~ 140 deg/sec at 180 MPH. The ailerons had little centering force. The roll mode was adequately damped and was deemed acceptable for the use case of the airplane. A dynamic roll test point consisting of a half-aileron deflection roll to 90° bank, followed by a rapid stick reversal to full-opposite aileron deflection to 0° bank was performed as a stress test, simulating an upset on the race course which necessitated maximum aileron to correct.

Adverse yaw was tested by performing "turns on one control," The pilot established coordinated, level flight and fixed the rudder pedals. Then, a slow aileron input was added and the initial nose yawing behavior was observed. During the design of the aileron control system, an aileron differential gearing of approximately 1.8/1.0 (Aileron up / Aileron Down) was applied to help counteract adverse yaw. With pedals fixed, while moving the stick to the left, no noticeable adverse yaw was observed. Conversely, while moving the stick to the right, the nose initially moved slightly to the left, indicating a small amount of adverse yaw. This was likely attributed to slight differences in aileron rigging.

Aircraft response after a rapid loss of power was explored to ensure no dynamic instabilities would be found in the event of an engine failure during a race where the aircraft would be close to the ground and in formation with other aircraft. Maintaining stable flight (desired ± 3° roll, ± 3° pitch, ± ¼ slip indicator deflection, adequate ± 6° roll, ± 6° pitch, ± 1/2 slip indicator deflection) using the stick and rudder, during an abrupt reduction of throttle from full power to idle, while flying at V_{RACE}, required minimal pilot compensation. The evaluating pilot achieved desired performance using rudders to visually keep the nose straight and aft stick to prevent the nose from dropping after the reduction of power (HQR 3).

LATERAL - DIRERCTIONAL

During phase 1 testing, a qualitative assessment on lateral-directional flying qualities was made. Directional stability with the stock wing was marginal, requiring constant attention and inputs to the rudder pedals in order to maintain coordinated flight. Directional stability was diminished further with the new wing, likely due to the significantly higher aspect ratio.

After the air races, the aircraft was brought through a phase 2 test program to more quantitatively evaluate lateral-directional flying qualities with a higher level of instrumentation. The added instrumentation included an INS to synthetically measure sideslip angle, pedal force sensors, and pedal displacement sensors. More information about this instrumentation can be found in the *Instrumentation* section.

Due to the cost constraints and difficulty mounting an air data probe on an aircraft of this type, measuring sideslip angle (β) was done synthetically using an inertial navigation system (INS). During tests requiring data collection of sideslip angle, a steady heading sideslip (SHSS) was always used as the baseline flight test technique. With the aircraft in a steady heading sideslip, aircraft heading was compared with ground track to estimate sideslip angle. To reduce errors due to wind, baseline laps were made on each sortie to characterize the local winds in the test area. The measured wind bias was then subtracted from the raw sideslip estimation to yield a corrected sideslip angle. To further reduce wind error, test flights collecting data in this manner were limited to 5 knots total surface wind. The pilot did not have the ability to monitor sideslip angle in real-time, so a smooth and steady roll angle and Ny were targeted by the pilot, which ultimately yielded a smooth β sweep.

After findings with the qualitative assessment performed during phase I, a deep dive into yawing moments in steady sideslips was performed and evaluated against MIL-F-8785C, paragraph 3.3.6.1.[6] A flight test technique consisting of a steady beta (β) sweep while maintaining a SHSS was used collect data. Each sweep resulted in sideslip angles from approximately -15° to +15°. These sweeps were accomplished slowly at a rate of approximately 1°β/sec so dynamic effects could be ignored. While an additional 5-7 degrees of rudder travel were available, unporting of the fuel system prevented flight at sideslip angles greater than ±15° due to fuel starvation and subsequent loss of engine power.

Examining pedal force for sideslip angles from -15°β to 15°β, there are three distinct sideslip angles where pedal force is zero: -10°β , 0°β, and +10°β. At -10°β and +10°β, the zero point is stable, allowing the airplane to remain at those sideslips angles with no pedal input. At 0°β, the zero point is unstable. Any disturbance of β will cause the airplane to depart from the 0°β condition and stabilize at either -10°β or +10°β. Inside the band of [-10°β to +10°β], the pedal force gradient is inverted, meaning positive pedal force (right pedal) is required to stay at positive sideslip angles less than 10° (wind in right ear).

Pedal deflection, directly related to rudder deflection for this aircraft, was also examined. Between the band of approximately -6°β to +6°β, the rudder deflection variation with sideslip angle is essentially zero, with the resolution of the data that was collected. This region indicates an area of neutral directional stability. Outside of this band, rudder deflection was essentially linear with sideslip (β) angle. Figure 14 illustrates these results.

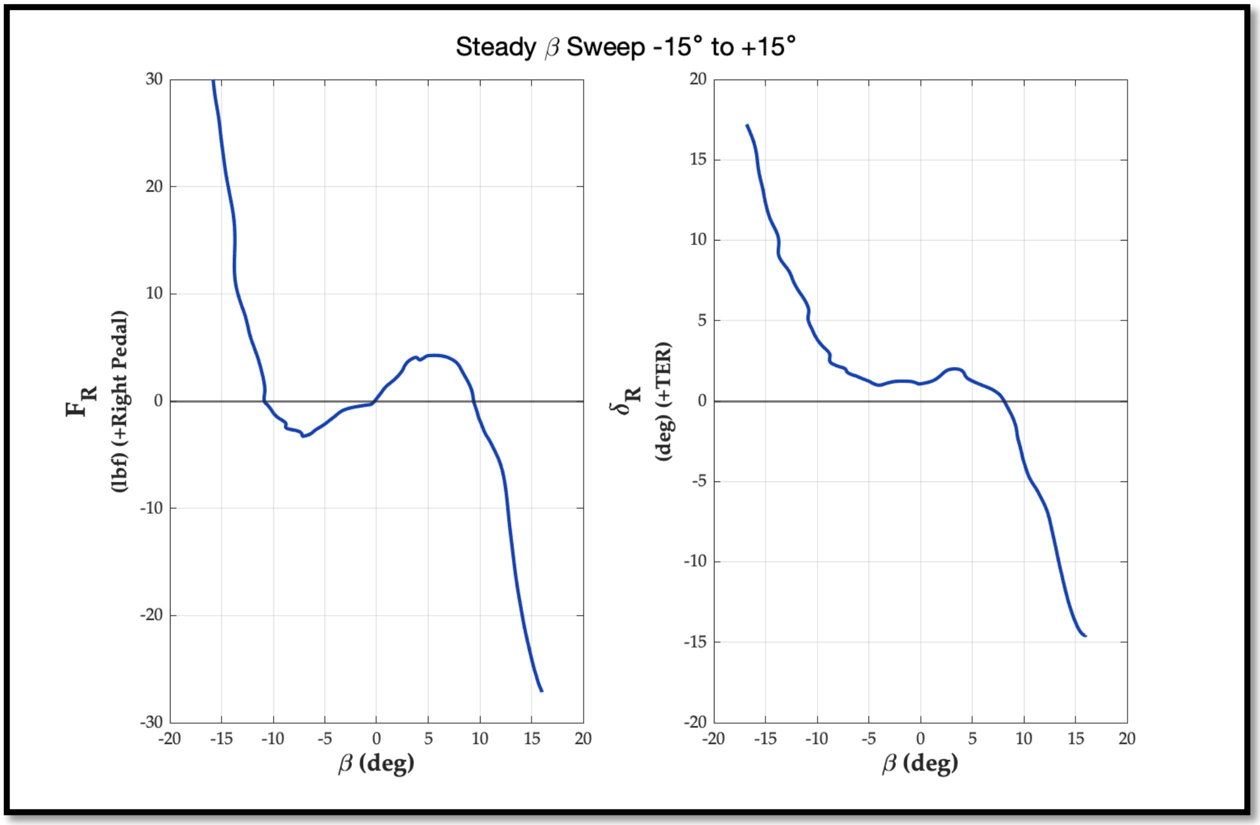


Figure 14: Pedal Force and Rudder Deflection Data During a β Sweep

To further examine the directional flying qualities of this aircraft, pedal releases were performed from zero-sideslip (β) flight at different airspeeds. At all tested airspeeds, (110 MPH, 140 MPH, and 190 MPH) the aircraft stabilized at -10°β or +10°β when pedal force was removed. The onset time for the full sideslip to develop once pedals were released was greatly influenced by airspeed, as shown in Table 1. Power setting changes did not vary these characteristics appreciably.

The aircraft did not seem to favor a certain direction, though biasing one side with a small yaw offset or yaw rate positively influenced the direction that sideslip would develop. As the aircraft stabilized at -10°β or +10°β, the sideslip angle would overshoot by 2-3° and positively damp in approximately 1-2 cycles. Figure 15 illustrates two pedal releases at 140 MPH, resulting in opposite direction sideslips.

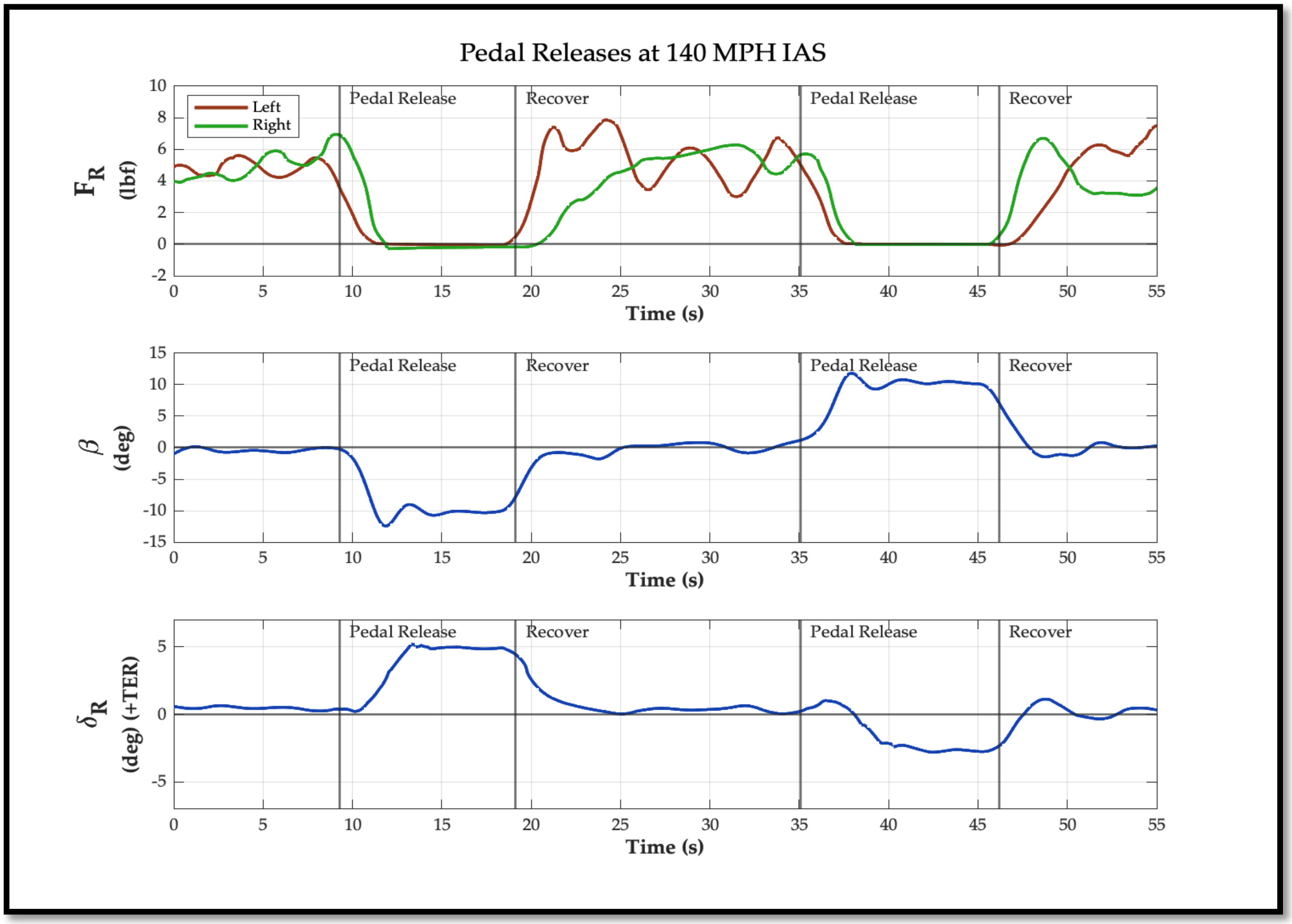


Figure 15: Pedal Releases at 140 MPH

Airspeed (MPH)	**Average Time (s)**
110	4.31
140	2.63
190	2.21

Table 1: Time to Establish -10 ° or +10 ° Sideslip After Pedal Release

Figure 15 also illustrates the pilot's constantly changing pedal forces in order to maintain zero sideslip while setting up for the test point. The evaluating pilot used the onboard slip/skid indicator and feel to constantly make small rudder inputs to achieve zero sideslip. This technique is required during virtually all flight conditions and maneuvers to prevent large sideslip excursions.

An attempt was made to characterize the dutch roll and spiral mode of the aircraft, but due to the unstable characteristics noted above, quality data was not able to be collected. Rudder doublets were used to characterize the dutch roll mode were started at 0°β, but resulted in the aircraft stabilizing at -10°β or +10°β. Rudder doublets were attempted with the center around +10°β, but depending on the magnitude of the inputs, the aircraft would swing over and re-stabilize on the other side at -10°β due to yaw inertia. While evaluating the spiral mode, pedal fixed test points could not be completed without large sideslip excursions due to the shallow rudder deflection vs sideslip angle gradient. Uncommanded changes in sideslip, even with pedals fixed, induced roll during these test points and made the spiral mode extremely difficult to characterize.

MIL-F-8785C, paragraph 3.3.6.1 states that for level 1 and 2 flying qualities, the following requirements apply…

- *"The variation of sideslip angle with yaw-control-pedal deflection shall be essentially linear for sideslip angles between +15 degrees and -15 degrees."[6]*
- *"The variation of sideslip angle with yaw-control-pedal force shall be essentially linear for sideslip angles between +10 degrees and -10 degrees."[6]*

Through the data collected on pedal force and pedal deflection, it is clear that the requirements above are not met, leading to the conclusion that the aircraft under test does not meet level 1 or level 2 flying quality requirements.

To determine if the directional flying qualities were acceptable for the intended mission, a handling quality test that involved completing 1 lap around a simulated race course at V_H was performed. Maintaining coordinated flight and level altitude (desired ± ¼ slip indicator deflection and ±25 ft altitude, adequate ± ½ slip indicator deflection and ±50 ft altitude) using rudder pedals required moderate pilot compensation. The evaluating pilot achieved desired performance using constant, small rudder inputs to keep the slip indicator centered (HQR 4).

The pilot compensation required to maintain coordinated flight during mission related maneuvers was moderate, and directional stability was deemed marginally acceptable for the intended mission.

Nz EXPANSION

As speed was expanded, the load factor envelope was also expanded using a build up approach. Nz was expanded in 0.5-1.0 g increments per flight to allow time for inspections and pilot g-tolerance training. For high g testing, wind up turns were used to precisely hit the g targets. To accomplish this, the pilot dove to accelerate to the calculated required airspeed, pulled the nose just above the horizon to avoid excessive pitch down attitudes, and roll 90-110 degrees to maintain a constant airspeed pull. A g onset rate of around 1-2 g/sec was targeted to help with adverse physiological effects associated with rapid g onset. The evaluating pilot reported an increased difficultly in sustaining g's above 5.0 in the Cassutt due to the upright seat angle, cramped cockpit, and little airflow as compared to other aerobatic aircraft that the pilot was familiar with such as the Extra 300L. During Nz expansion, the stick force per g gradient was found to be shallow and an estimated stick force at 6 g of 12-15 LB.

For the 6 g test point, the maneuver needed to be started at over 220 MPH due to the stall speed increase due to Nz. A relatively small band between the margined accelerated stall speed at 6.0 g and the cleared flutter speed existed and made the 6.0 g test point challenging for the evaluating pilot to achieve accurately. During the 6 g test point, the evaluating pilot took four tries to achieve 6.0 g. The previous three attempts had undershot the target by 0.2-0.1 g. This was due to the pilot's conservatism in ensuring the airplane did not exceed the 6.0 g target in an effort to keep the airplane below the maximum tested flutter speed and above the margined accelerated stall speed. After achieving the 6.0 g test point on the fourth and final attempt, the pilot reported fatigue from multiple high g test point attempts. A post-flight review of the attempts highlighted the importance of balancing the completion of a test point with pilot physiological factors, especially during physically demanding test points that carry elevated risk.

STALL TESTING

The scope of stall testing was limited due to the uncertain spin recovery ability of this airplane due to its small tail and higher aspect ratio wing. Determining 1 g stall speed and 1 g stall characteristics were necessary. This new wing was aerodynamically elliptical, which offers undesirable stall characteristics at the expense of lower induced drag. On typical airplanes with rectangular wings, the stall is benign and "mushy feeling" because the stall originates at the roots and travels out to the tips. The theory behind an elliptical wing says that since the chord changes at the same rate as the desired lift coefficient, each local airfoil section should exceed the critical lift coefficient when the global lift coefficient is exceeded, meaning the entire wing should stall at once. This theory was verified during stall testing.

The approach to the stall was done slowly (1 MPH/sec) to eliminate any dynamic effects. Leading up to the stall, the wing was controllable and offered little warning besides the positive and excessive stick position. At 76 MPH IAS, the wing produced a sharp and audible "pop" with a simultaneous, uncommanded pitch down as the flow separated from the wing all at once. After completing five power-off stalls, the evaluating pilot noted that roll off was sensitive to small amounts of sideslip. When entering the stall with minimum practical sideslip, the aircraft did not favor a roll off in a particular direction. The stall was easily recoverable by unloading the stick, straightening the nose with small rudder inputs, and adding power. It was determined that stall characteristics were as expected but reenforced the need to never approach a stall in an uncontrolled environment with this wing. An unexpected stall, paired with weak directional stability, has the potential to result in rapid departure from controlled flight.

CONCLUSION

The journey through the build and test of the new, modified formula one racing wing brought many firsts and lessons learned. The new wing was taken through a set of ground and flight tests to prove its readiness for pylon air racing. A ground static load test verified the finite element model, as well as proved the manufacturing workmanship. After the wing was integrated into a stock Cassutt fuselage, the aircraft entered the flight test phase where it was tested for qualities important for pylon air racing such as flutter, certain flying qualities, load factor expansion, and drag reduction. Through the ground and flight test campaign, the aircraft met all test objectives and was deemed safe to use in pylon air racing.

FUTURE TESTING

Due to the reduced test scope associated with preparing for the Reno Air Races, several desired test objectives were deferred. Stall testing in different configurations, such as accelerated stall and stalls in turns is desired to further collect data on elliptical wing behavior near and after a stall. In addition, a performance test campaign could be informative to quantify the capabilities of the aircraft to be able to operate outside the test environment. Further analysis on the factors that contribute to the unique lateral-directional flying qualities of this aircraft is also desired. In an effort to reduce energy losses due to sideslip induced drag during a race, a custom yaw augmentation system implementation will be considered. Lastly, the author would like to conduct performance testing on modifications to the fuselage, canopy, cowling, and empennage to improve the aircraft’s speed around a formula one race course.

LESSONS LEARNED

Although the test campaign was executed relatively smoothly, several lessons were realized or learned.

Procedural dry runs are immensely important for ensuring a smooth test. Prior to the first flight, the team practiced towing the airplane around the airport, performed preflight checkouts, and rehearsed radio communications for the flight. Small issues like making sure the tow truck has the right size hitch were realized before flight day. It was important to ensure the only untested part of the flight test day, was the flight itself. **Dry running procedures is crucial for preparing the team for a flight test and buys down risk for on-the-fly troubleshooting during an already stressful test.**

Set limits on the number of times you can attempt a test point prior to the test. During the long-anticipated 6.0 g test point, the evaluating pilot took four tries to achieve the test condition. During the flight, the pilot reported that fatigue was setting in, though elected to continue trying to complete the test. The consequence of diminished focus due to fatigue during a physically demanding test point could lead to poor decision making and even catastrophic, if g induced loss of consciousness had occurred. **Define attempt limits for test points with elevated risk and stick with them in flight.**

The first landing attempt was unsuccessful and resulted in a go-around due to wing and tail incidence being inadequately set. A dedicated stability and control analysis was not performed on this aircraft due to time constraints and assumed similarity to other aircraft designed and tested by members of the team. Had an analysis been performed, wing and tail incidence could have been set to more appropriate setting and reduced the risk of an unsuccessful landing. **Perform a stability and control analysis for all unique aircraft first flights, even ones with assumed similarities.**

The decision making trades for the first flight profile (short hop on the runway vs. commit to flight) were discussed earlier in the paper. The team had ultimately made the decision to commit to flight during the first test to separate the two highest risk phases of the flight; takeoff and landing. This decision proved to be wise when the first landing attempt needed to be aborted due to a pilot induced oscillation shortly after touchdown that was discussed earlier in this paper. Had the pilot elected to attempt the “short hop”, the first landing could have been similar which would have resulted in an unplanned abort to flight scenario or loss of control on the ground. **Unless special conditions warrant a “short hop” type first flight, it was found that getting away from the ground quickly and exploring the handling characteristics of the airplane at a safe altitude before attempting a landing was beneficial.**

APPENDICIES

APPENDIX 1 : PHASE I TEST REQUIREMENTS

GROUND TEST REQUIREMENTS (REQUIRED PRIOR TO F01)

G1.1: The ailerons shall be 100% statically balanced in flight configuration.

G1.2: The center of gravity shall be between 8-25% MAC in all operable mass loading conditions.

G1.3: The wing shall be proof loaded to 7x the airplane's gross weight with distributed loading representative of flight loads.

FLIGHT TEST REQUIREMENTS

F1: **The aircraft shall be controllable throughout its normal range of speeds and throughout all the maneuvers to be executed.**

F1.1: The aircraft shall be controllable at slow speeds ($1.05V_S$ – $1.25V_S$)

F1.2: The aircraft shall be controllable at normal climb and cruise speeds ($1.25V_S$ – V_H)

F1.2: The aircraft shall be controllable at high speeds ($1.25V_H$)

F2: **The aircraft shall have no hazardous operating characteristics.**

F2.1: The aircraft shall be free from flutter for any condition of operation within the limit V-n envelope.

F2.2: The aircraft shall demonstrate flight at enveloping load factors.

F2.2.1: The aircraft shall demonstrate flight at a load factor of +6 (+.25/-0)

F2.2.2: The aircraft shall demonstrate flight at a load factor of -1 (+0/-.5)

F2.3: The aircraft shall have adequate stall characteristics.

F.2.3.1: The aircraft must produce and correct roll by unreversed use of the rolling control, up to the time the aircraft stalls.

F2.3.2: The aircraft must produce and correct yaw by unreversed use of the directional control, up to the time the aircraft stalls.

F2.3.3: The aircraft must demonstrate a positive stick force curve up to the stall.

F2.3.4: The aircraft shall demonstrate a stall recovery to level flight by normal use of the flight controls without increasing power.

F2.4: The aircraft shall have acceptable flying qualities.

F2.4.1: The aircraft shall show any short period oscillation between Vs and Vh is damped with primary controls fixed.

F2.4.2: The aircraft shall have a roll rate of at least 100dps at Vh and 60dps at Vapp.

F2.4.3: The aircraft shall not have any adverse handling characteristics that unreasonably increase pilot workload with a rapid loss of power at Vrace and Vapp.

F2.4.4: The aircraft shall demonstrate a linear yaw-control-pedal force correlation to sideslip angles.

F2.4.5: The aircraft shall demonstrate acceptable short period pitch response in race configuration (180 deg, level, 2G turn at max power) by maintaining altitude (desired ±25 ft , adequate ±50 ft)

F.2.4.6: The aircraft shall demonstrate the ability to maintain coordinated flight (desired ± ¼ slip indicator deflection, adequate desired ± ½ slip indicator deflection) during a simulated race lap.

F3: **The aircraft shall demonstrate and comply with IF1 flight demo requirements.**

F3.1: The aircraft shall demonstrate a 6 "G" pullup

F3.2: The aircraft shall demonstrate a dive at $1.1V_H$

F3.3: The aircraft shall demonstrate aileron rolls in each direction.

F3.4: The aircraft shall demonstrate a half roll left followed by a half roll right.

F4: **The aircraft shall be "race ready"**

F4.1: The aircraft shall demonstrate maneuvers at speeds at 110% of Vrace

F4.1.1: The aircraft shall demonstrate level turns up to 3.0G

F4.1.2: The aircraft shall demonstrate a roll maneuver with >50% aileron deflection with immediate aileron reversal at 75 degrees back to wings level.

F4.2: The aircraft shall be tested for glide performance.

F4.2.1: The aircraft shall be tested for glide performance from an altitude no less than 3000ft AGL.

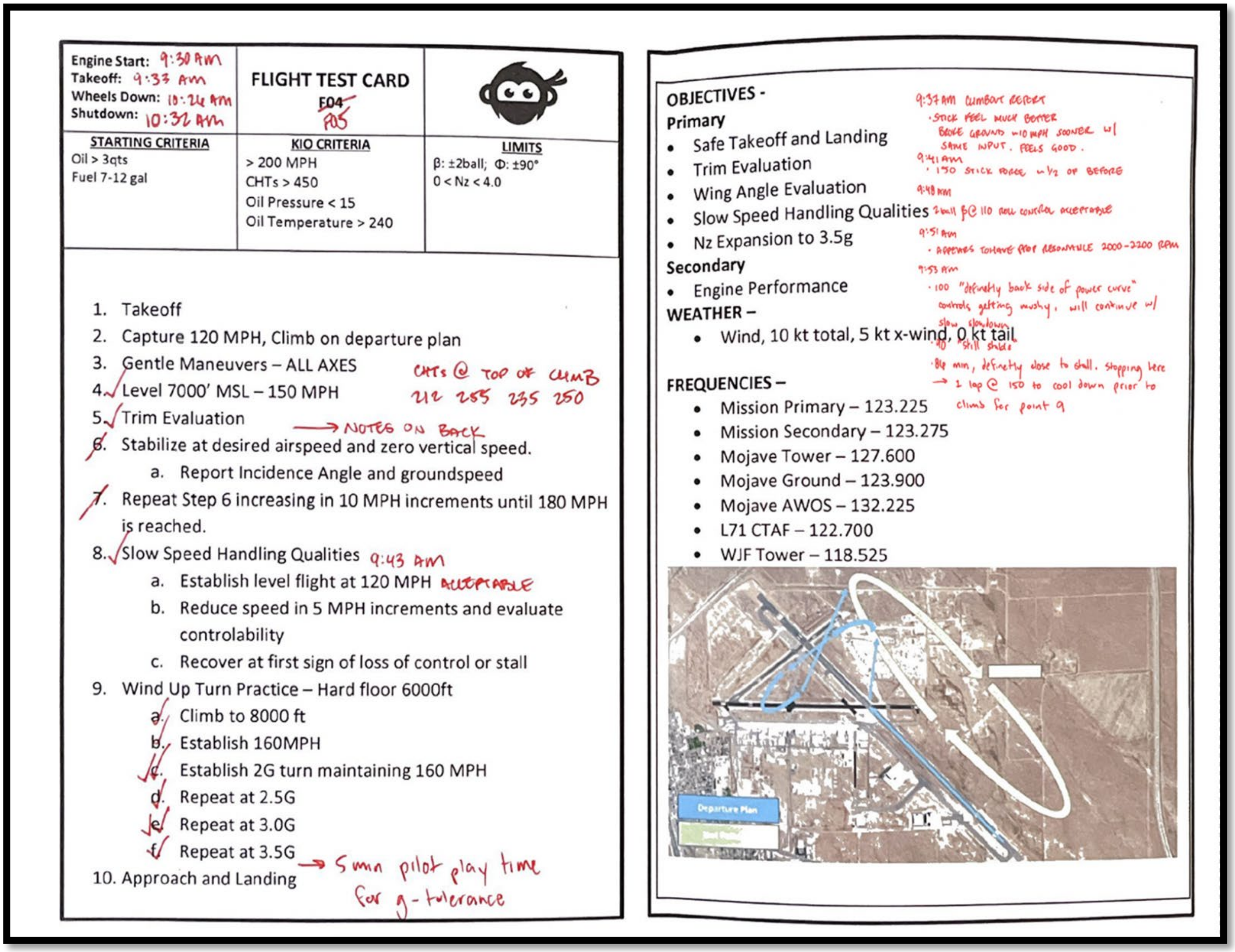
F4.2.2: The aircraft shall be tested for glide performance from an altitude no greater than 100ft AGL.

F4.3: The aircraft shall be trimmed such that 1-2lbf of forward stick force is required to maintain altitude at Vrace.

APPENDIX 2 : PHASE II TEST OBJECTIVES

1. Characterize yawing moments in steady sideslips
    a. Evaluate variation of sideslip angle with pedal deflection
    b. Evaluate variation of sideslip angle with pedal force
    c. Evaluate effect of power setting
2. Characterize rolling moments in steady sideslips
    a. Evaluate variation of roll-control deflection and force with sideslip angle
    b. Evaluate variation of bank angle with sideslip angle
3. Characterize aircraft roll mode
    a. Collect data on roll mode time constant at various speed levels
    b. Collect data on maximum roll rate at various speed levels
4. Characterize aircraft spiral mode
5. Characterize aircraft dutch roll mode
    a. Collect data for dutch roll frequency and damping with controls fixed
    b. Collect data for dutch roll frequency and damping with controls free

APPENDIX 3 : FLIGHT CARD EXAMPLE



Engine Start: 9:30 AM
Takeoff: 9:33 AM
Wheels Down: 10:24 AM
Shutdown: 10:32 AM

FLIGHT TEST CARD
~~F04~~ F05

STARTING CRITERIA	KIO CRITERIA	LIMITS
Oil > 3qts Fuel 7-12 gal	> 200 MPH CHTs > 450 Oil Pressure < 15 Oil Temperature > 240	β: ±2ball; Φ: ±90° 0 < Nz < 4.0

1. Takeoff
2. Capture 120 MPH, Climb on departure plan
3. Gentle Maneuvers – ALL AXES
4. Level 7000' MSL – 150 MPH
5. Trim Evaluation → NOTES ON BACK
6. Stabilize at desired airspeed and zero vertical speed.
    a. Report Incidence Angle and groundspeed
7. Repeat Step 6 increasing in 10 MPH increments until 180 MPH is reached.
8. Slow Speed Handling Qualities 9:43 AM
    a. Establish level flight at 120 MPH ACCEPTABLE
    b. Reduce speed in 5 MPH increments and evaluate controlability
    c. Recover at first sign of loss of control or stall
9. Wind Up Turn Practice – Hard floor 6000ft
    a. Climb to 8000 ft
    b. Establish 160MPH
    c. Establish 2G turn maintaining 160 MPH
    d. Repeat at 2.5G
    e. Repeat at 3.0G
    f. Repeat at 3.5G → 5 min pilot play time for g-tolerance
10. Approach and Landing

CHTs @ TOP OF CLIMB
212 255 235 250

OBJECTIVES -

Primary

- Safe Takeoff and Landing
- Trim Evaluation
- Wing Angle Evaluation
- Slow Speed Handling Qualities
- Nz Expansion to 3.5g

Secondary

- Engine Performance

WEATHER –

- Wind, 10 kt total, 5 kt x-wind, 0 kt tail

FREQUENCIES –

- Mission Primary – 123.225
- Mission Secondary – 123.275
- Mojave Tower – 127.600
- Mojave Ground – 123.900
- Mojave AWOS – 132.225
- L71 CTAF – 122.700
- WJF Tower – 118.525

9:37 AM CLIMBOUT REPORT
· STICK FEEL MUCH BETTER
BROKE GROUND ~10 MPH SOONER W/ SAME INPUT. FEELS GOOD.
9:41 AM
· 150 STICK FORCE ~1/2 OF BEFORE
9:48 AM
2 ball β @ 110 roll control acceptable
9:51 AM
· APPEARS TO HAVE PROP RESONANCE 2000-2200 RPM
9:53 AM
· 100 "definetly back side of power curve" controls getting mushy. will continue w/ slow slowdown
· 90 "still stable"
· 84 min, definetly close to stall. stopping here
→ 1 lap @ 150 to cool down prior to climb for point 9

ACKNOWLEDGEMENTS

The author thanks all the collaborators of the Monkey Ninja wing project. Thank you to all of the Cal Poly students who provided hours of essential help during the build phase to get the project done on time. Thank you to Tres Clements and Aerocrafted for providing a space and the resources to build and assemble the wing. Thank you to the flight test and Reno crew, that helped to integrate, safely test, and operate the airplane for the 2023 Reno Air Races. In particular, the author would like to thank Dr. Paulo Iscold for the use of his design and his mentorship in technical topics and beyond during the entire course of the project.

Figure 16: The Cal Poly student build crew and flight test crew pose for a picture at the 2023 Reno Air Races

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